

## Final Report

**"Numerical Model Studies of the Martian Mesoscale Circulations" - NAGW-4060**

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**I. INTRODUCTION**

The study objectives were to evaluate by numerical modeling various possible mesoscale circulation on Mars and related atmospheric boundary layer processes. The study was in collaboration with J. Tillman of the University of Washington (who supported the study observationally). Interaction has been made with J. Prusa of Iowa State University in numerical modeling investigation of dynamical effects of topographically-influenced flow.

Modeling simulations included evaluations of surface physical characteristics on: (i) the Martian atmospheric boundary layer and (ii) their impact on thermally and dynamically forced mesoscale flows. Special model evaluations were made in support of selection of the Pathfinder landing sites. J. Tillman's finding of VL-2 inter-annual temperature difference was followed by model simulations attempting to point out the forcing for this feature. Publication of the results in the reviewed literature is pending upon completion of the manuscripts in preparation as indicated later.

**2. INVESTIGATIONS****a) Numerical models aspects**

- (i) The prime numerical mesoscale model in the study was that of Arritt (1989), which was adjusted to account for Martian processes. This included prescribing Martian constants, and replacement of radiative transfer computations following Savijarvi (1991). The radiative transfer scheme originally utilized in Ye *et al.* (1991) was replaced in the new code. The radiative transfer scheme accounts for CO<sub>2</sub> and dust effect on solar irradiance, and CO<sub>2</sub> infrared transfer using an emissivity scheme.
- (ii) The various situations which were selected for 1-D sensitivity simulations required a large number of simulations. For these simulations we adopted the procedure outlined in Segal *et al.* (1993). This procedure utilizes a virtual 3-D domain in order to generate multiple 1-D simulations.
- (iii) An anelastic approximation is used with a novel, time variable coordinate transformation to formulate a transient, two-dimensional mathematical model to describe the evolution of gravity waves generated in the lower atmosphere (Prusa *et al.*, 1996). The model was adjusted to simulate the dynamical effects of the Martian steep terrain on strong

background flows. The model has been used to compute transients that mimic flow near the great shield volcanoes of Tharsis and over the Claritas Fossae ridge.

## **b) Simulation results**

### **(b.1) *Multiple 1-D simulations of the boundary layer and surface processes***

The surface sensible heat flux,  $H_s$ , is the main thermal forcing in the circulations addressed in this research. Therefore, emphasis was given in the simulations to evaluate its magnitude for a range of relevant conditions. In addition, the simulations provided insight into: (i) diurnal evolution of the Martian atmospheric boundary layer, (ii) evaluation of the 1.6 m height air temperature and comparisons with the Viking Landers observation, (iii) evaluation of the daytime convective scaling velocity  $W'$ . The simulations were carried out for various combinations of background wind speeds  $U_0$ , roughness parameter  $Z_0$ , surface albedo, and soil physical properties. These multiple 1-D simulations were carried out to explore seasonal and latitudinal effects. For this purpose composites of various wind speeds and latitudes ( $0^\circ$ ,  $15^\circ\text{N}$ ,  $30^\circ\text{N}$ ,  $45^\circ\text{N}$  and  $60^\circ\text{N}$ ) were considered for  $L_s = 0^\circ$ ,  $90^\circ$  and  $270^\circ$  ( $L_s$  - the areocentric longitude). The model was integrated until convective-radiative equilibrium was reached (about 5 days). Evaluation of the importance of the absorbed solar and longwave irradiance on the boundary layer were included. The composites quantified comprehensively the investigated characteristics; for example, the increase in sensible heat flux  $H_s$  with the increase of wind speed or surface roughness and their dependence on season and latitude. The 1.6 m air temperature and the daytime convective boundary layer depth showed similar patterns. Interactively with J. Tillman, comparisons have been made with the Viking Landers data, the analysis results reported in Tillman *et al.* (1994) and additional observed data. We found general agreement between model results and the available observed data. Evaluations reported in Segal *et al.* 1996, aided the understanding the pattern of temperature drop observed at Landers sites following sunset.

An important daytime convective boundary layer (CBL) parameter is the convective scaling velocity,  $W'$ .  $W'$  provides an estimate of the average upward velocities of the large eddies within the CBL. Its peak values reached 4.5 m/s during the summer in mid-latitudes corresponding to the peak in  $H_s$ .

Rock abundance may reach 30% in some locations; therefore, characteristics of the surface thermal stratification may be affected. Simulations have been carried out to explore such impacts. The simulations indicated substantial diurnal difference in surface temperature for the rock surfaces compared with typical soil surfaces. This implies that suppression of the nocturnal surface layer temperature inversion should be pronounced in rocky regions.

Results obtained in the multiple 1-D simulation were used in the conceptual evaluations of Martian planetary boundary layer/climatology station presented in Tillman *et al.* (1994).

### **(b.2) *Numerical model simulations of thermally induced mesoscale circulation of Mars***

2-D simulations have been carried out to provide insight into several situations that were suggested in the proposal.

#### **(i) *Polar cap breezes.***

One of the research objectives is evaluation of the thermally induced breezes near the polar cap edge (due to the contrast of CO<sub>2</sub> ice covered ground with bare soil). Simulations were carried out for spring, and included situations with: flat terrain (with sharp and gradual change in the ice edge), background flows, and slopes. The effect of the Coriolis force on veering of the flow is pronounced, as anticipated in such high latitudes. The simulated wind speeds for flat terrain and "sharp edge" were as high as  $\sim 15 \text{ m}\cdot\text{s}^{-1}$  (at  $\sim 300$  AGL), though the equatorward component peak is only  $10 \text{ m}\cdot\text{s}^{-1}$ . Gradual deepening of the boundary layer while moving away from the ice edge was evident through the potential temperature stratification. When combined with slope (of aspect ratio 0.005), as may be the case in several locations, substantial weakening of the ice breeze due to opposing thermal daytime upslope flow was simulated. Combined with a supportive intense large scale flow ( $15 \text{ m}\cdot\text{s}^{-1}$ ) the intensification of the ice breeze was mild in the flat terrain case, but pronounced (doubling of the flow) when combined with slope.

(ii) *Thermal circulation due to variations in surface albedo and surface roughness.*

On Mars horizontal gradients in  $H_s$  within mesoscale domains are likely to develop in various situations. Consequently thermal circulation (TC) should be induced. We simulated summer day TC development due to several scenarios of variation of surface albedo. For example: step function change of 0.2 and 0.3 in the albedo, and a corresponding gradual change along 100 km. With the step function change noticeable low-level gradients of the potential temperature were developed and consequently TC with flow speed as high as  $6 \text{ m}\cdot\text{s}^{-1}$  was induced. The flows reduced by more than 50% for the case of gradual changes in the albedo.

TC situation related to a horizontal variation in the surface roughness ( $Z_0$ ) between 0.2 cm to 1 cm showed noticeably weaker induced flow than the surface albedo related situation.

Observational evaluation of Earth's mesoscale thermal circulations which are physically equivalent to these in (i)-(ii) have indicated that they are likely to be noticeably weaker than those suggested by numerical modeling. Given this conclusion in the Earth situation, we are further evaluating the modeling results for the Martian circulations, before the results are documented in a paper.

### **(b.3) Mesoscale topographical effects on Martian Flows**

(i) *Low-level jets in the near equatorial latitudes*

Previous studies indicated that western boundary currents (WBC) occur in the Martian atmosphere in the presence of large longitudinal topographical gradients, combined with  $\beta$  effect. It was suggested that when induced upslope flow has a meridional component, it would reinforce or reduce the simulated WBC. Such an effect is likely to occur in the eastern side of Syrtis ( $10^\circ\text{N}$ ) where upslope flow induced by latitudinal slope would reinforce the WBC. However, even if the slope is purely longitudinal, towards the end of the daytime and during the nighttime meridional component of the thermally induced flow resulting from inertial oscillations would reinforce or reduce the flow (depending on slope orientation and latitude). We explored these characteristics by scaling and by numerical modeling. The evaluations were carried out for various latitudes and slope inclinations.

A case study in which southerly background flow of  $15 \text{ m}\cdot\text{s}^{-1}$  was prescribed is described in the following, exemplifying characteristic features of the simulated low level jets. A ridge (aspect ratio of  $\sim 0.01$ ) located at  $30^\circ\text{N}$  with west and east facing slopes was considered. The upslope components were asymmetric due to adjustment of the Coriolis and frictional forces. Return circulation cells are simulated. The difference in the  $v$  component between both slopes was small. By sunset intense upslope flow was simulated, attributable to cessation of turbulence, while the asymmetric structure became more pronounced. By that time some clockwise veering of the upslope component occurred supporting the east facing slope  $v$  component and reducing that in the west facing slope. From this time, inertial oscillations of the flow are almost unaffected by the thermal gradient above the elevated slopes. By midnight shallow downslope flow in the slope direction is simulated, where lack of significant cross slope component aloft implies a completion of more than southward veering. This is supported by the respective intensification in the eastern slope  $v$  component and initiation of the strengthening of the  $v$  component in the east facing slope. Further veering of the late afternoon  $u$  component resulted in continuation of this pattern by sunrise. The overshooting of the  $v$  component reached at least  $7 \text{ m}\cdot\text{s}^{-1}$ .

Presently we are evaluating comprehensive observational data for a similar low-level jet situation on Earth which should provide further insight into the nature of the Martian low-level jet situation. Subsequently the results obtained in the Martian case will be published.

(ii) *Dynamical intensification of flow by steep terrain*

We investigated two-dimensional topographical forcing as a possible mechanism for generating severe downslope windstorms (SDW's) sufficient to raise dust off of the surface using the gravity wave model of Prusa et. al. (1996). A series of simulations (Prusa and Segal, 1997) demonstrated that wave development is strongly dependent upon the Froude number,  $Fr = u_0 / (A * N)$ ; and to a lesser extent, the topography aspect ratio,  $R = A / S_x$ . Here  $u_0$  denotes the basic state wind;  $A$  the obstacle height above the surroundings and  $S_x$  its horizontal scale; and  $N$  the Brunt-Vaisala frequency.

Our SDW results agree closely with previously reported experiences of the (Earth) tropospheric community (Klemp and Lilly, 1977; Clark and Peltier, 1984). In particular, Froude numbers of  $\sim 1$  are required for nonlinear resonance of the wavefield to develop, with subsequent wave activity becoming so strong that the waves break very near the mountain. Our simulations for  $Fr \sim 1$  show zonal wind perturbations roughly equal in magnitude to the basic state wind itself (i.e., the perturbed wind field varied from zero to double the basic state wind). The flow field was highly unsteady, and consisted of vortices forming over the peak and being shed downstream. For cases with  $Fr \gg 1$ , nonlinear growth and wavebreaking still occurred, but aloft and far above the surface. Although of little concern for dust raising events, this may be of fundamental importance in polar warming events (gravity wave forcing is known to reverse the mesopause temperature gradient on Earth) and warrants future study. For  $Fr \ll 1$ , the resonance that is the hallmark SDW's cannot occur. The importance of aspect ratio is that small values ( $R \ll 1$ ) tend to excite internal waves whereas larger values of  $R$  encourage potential flows, for given values of  $Fr$ .

Froude number scaling arguments based upon these simulations indicate that in order to generate near surface winds of  $50 \text{ m}\cdot\text{s}^{-1}$  required for saltation, given a basic state of  $25\text{-}30 \text{ m}\cdot\text{s}^{-1}$ , that the topographical amplitude must satisfy  $A \sim 20/N$ . Clearly activation of the lowest

height topography requires the greatest possible atmospheric stability,  $N \sim 0.01 \text{ s}^{-1}$ . Such conditions are more favored at night. Thus a minimum topographical height of about 2 kms seems necessary to produce SDW's capable of raising dust from the surface. This conclusion contradicts a recent result by Magalhes and Young (1995) which indicates that saltation inducing SDW's can occur over much smaller ridges of 10-100 m height. Observations (from Earth in 1973, Martin 1976; and from Viking Orbiter in 1976, Briggs et. al. 1979) have revealed nascent dust storms arising in the Claritas Fossae region (at least) by mid morning. Claritas Fossae is a 1.5 to 2.5 kms high ridge running for several hundred kms NW to SE near +100 longitude and -30 latitude. As Claritas Fossae is one of the most active dust forming regions on Mars (Martin and Zurek, 1993), it is of interest to note that it satisfies the height and time constraints that our study suggest are appropriate for SDW's on Mars. Additional simulations are presently being conducted to help clarify the parameter space ( $Fr$ ,  $R$ ,  $u_0$ , and  $H_i$ ) in which SDW's may develop in this region of Mars ( $H_i$  is the potential temperature scale height). Details of these results are being reported in Prusa and Segal (1997).

#### **(b.4) Additional model investigations**

##### **(i) *Inter-annual temperature differences at the Viking L-2 site***

J. Tillman pointed out that for sols from 669-969 (Summer-Autumn) at Viking L-2, the daily maximum temperature  $T_{\max}$  is consistently several degrees higher than during the same season of the first year, while the minimum temperature  $T_{\min}$  is essentially identical. Further analysis by J. Tillman most recently provided diurnal refinement for this temperature difference. Understanding of the cause for the persistent temperature difference was pursued through model simulations.

Multiple 1-D simulations were carried out to examine the hypothesis that the above temperature differences were due to the slightly different dust optical path between the two periods. No confirmation for this hypothesis was obtained by the simulations results. Seasonal changes of the winds between these two periods are examined as additional causes for the difference.  $T_{\max}$  was found to increase about linearly with the wind speed. On the other hand at 0300 MST (when about the daily minimum temperature is obtained) no dependency on wind speed is simulated. However persistence increase in the wind speed in the second year which might provide explanation to the inter-annual temperature difference is not found in the corresponding wind speed observations. Sensitivity simulations were also carried out to evaluate the impact of small changes in surface albedo because of dust deposition/saltation on  $T_{\max}$  and  $T_{\min}$ . These were found to be relatively small considering the simulated range of variation in the albedo (0.05).

Further evaluations are carried out and the final results will be published in a subsequent paper.

##### **(ii) *Thermal dissipation of cold air mass outbreaks***

Tillman et al. (1979) reported on an identified passage of a cold front in the Viking L-2. Development of frontal systems in the Martian atmosphere has been assumed to be reduced due to the short radiative relaxation time. In model simulations we evaluated the role of increased sensible heat flux while cold air masses advected during the daytime on warm surfaces. Various latitudes and wind speeds were considered (during winter and spring), while the modification in the air mass thermal stratification was evaluated using a Lagrangian

approach. It was found that the sensible heat flux may increase by more than 100% and may result in a noticeable daytime thermal dissipation of a typical cold front. In the case of early spring outbreaks of cold air masses from the polar CO<sub>2</sub> ice cap, it would be associated over the ice free area with deepening of the CBL and potential for downward fluxes of momentum, which may enhance the potential for local dust storms. Detailed results are reported in Segal et al. (1997).

*(iii) Evaluations in support of the Pathfinder mission meteorology*

Boundary layer characteristics and winds at the initial potential Pathfinder near-equator locations were estimated from model runs and Viking data support of site selection. These Viking planetary boundary layer observations and model inferences were presented at the Pathfinder site selection meeting at JPL on 9,10 June 1994. Prior to this meeting, it was perceived that thermally induced flow near the equator may reach extremely high values. At the landing season,  $L_s = 145^\circ$ , an optical depth,  $\tau = 0.4$  from Viking Lander 1 data, was chosen as representative of this latitude. Heat flux and wind speed (at 1.6 meters and versus height) and potential temperature, were calculated as a function of: 1)  $z_0$  and geostrophic wind, 2) height and geostrophic wind, and 3) height and  $z_0$ , for four times a day for a flat site. The same calculations were performed for a sloping terrain between two level sites to simulate the slope winds of the Chryse basin using both zero and  $5 \text{ m s}^{-1}$  geostrophic wind speed.

Increased surface sensible heat flux with wind speed resulted in the deepening of the CBL. Surface nocturnal temperature inversion is simulated in the lower hundred meters above surface, while slight thermal stabilization is simulated above this layer. Some intensification of the wind in the lower 1 km was simulated (boundary layer nocturnal jet).

Simulated slope flows (slope inclination 0.005) in potential Pathfinder sites were examined for various background wind conditions. When background flow is not considered ( $u_g = 0 \text{ m s}^{-1}$ ), the upslope thermal flow reached a peak of  $7 \text{ m s}^{-1}$  in the late afternoon. Around sunrise drainage flows were simulated in the first several hundred meters above the surface with peak of  $4 \text{ m s}^{-1}$  near the surface. When upslope background flow ( $5 \text{ m s}^{-1}$ ) was included in the simulations, the late afternoon upslope flow reached peak of  $12 \text{ m s}^{-1}$ . During the night the coupling of the thermally induced drainage flow with the opposing background flow reduced the flow intensity along the slope. Around sunrise a very shallow layer ( $<100 \text{ m}$ ) of drainage flow was simulated.

Tillman showed that the Viking Lander 1 hourly mean wind speed was a maximum of  $12.2 \text{ m s}^{-1}$  at the 1.5 meter sensor height, during the same season. Assuming that its slope is greater than that of the Pathfinder prospective sites, the Pathfinder winds would be similar or less, based only on this information, which is consistent with the numerical model simulated flow.

These results were presented at the Second Mars Pathfinder Project Science Group Meeting, JPL, 9-10 June, 1994, and are contained in the meeting notes, pages 198-242.

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#### **4. REPORTS AND PUBLICATIONS SUPPORTED BY GRANT NAGW-4060**

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